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Effects of Shielding on Gamma Rays

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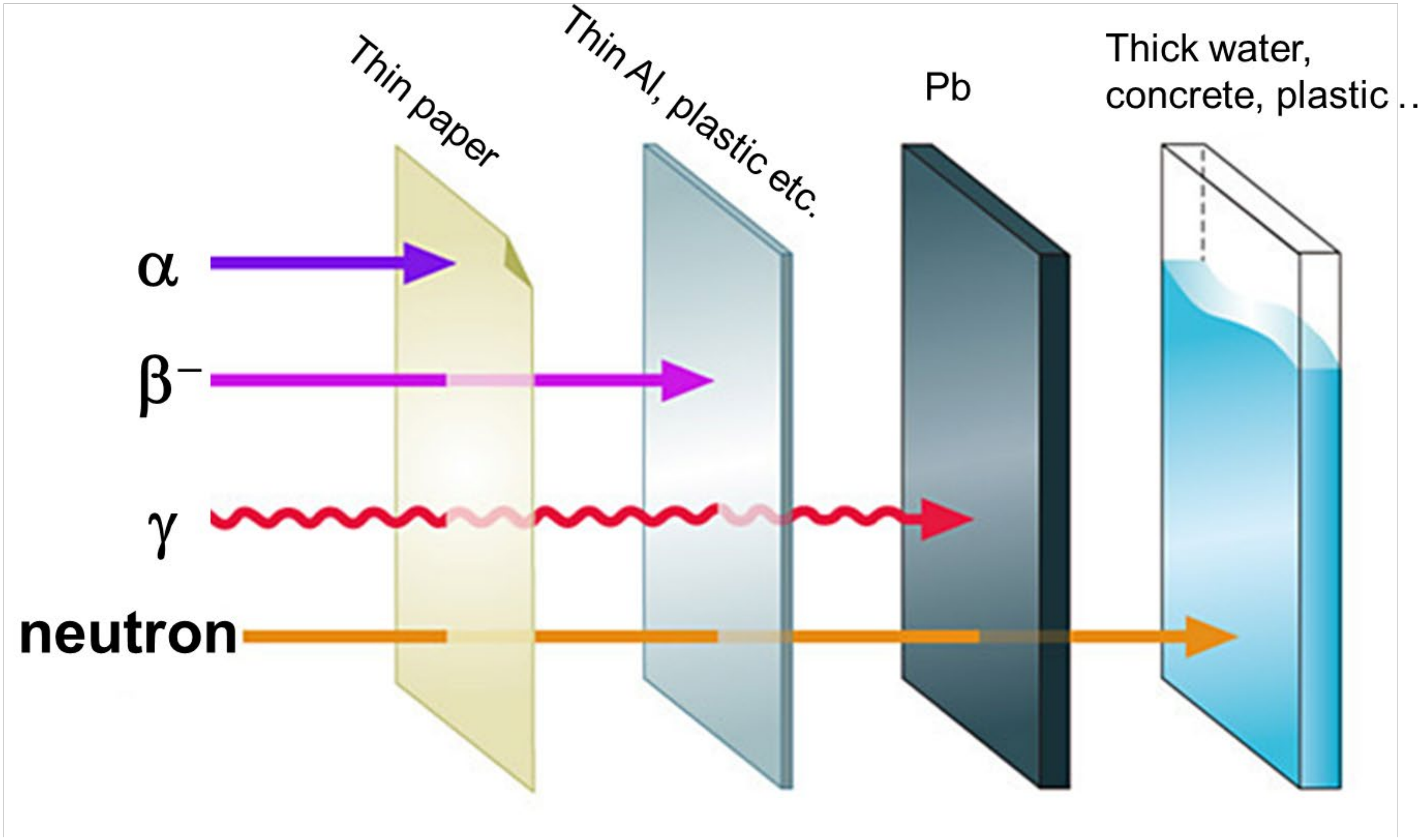
Introduction

- The interaction of gamma rays with matter results in an effect we call attenuation (i.e. ‘shielding’)
- Attenuation can dramatically alter the appearance of a spectrum
- Attenuating materials may actually create features in a spectrum via x-ray fluorescence

Radiation Types and Shielding

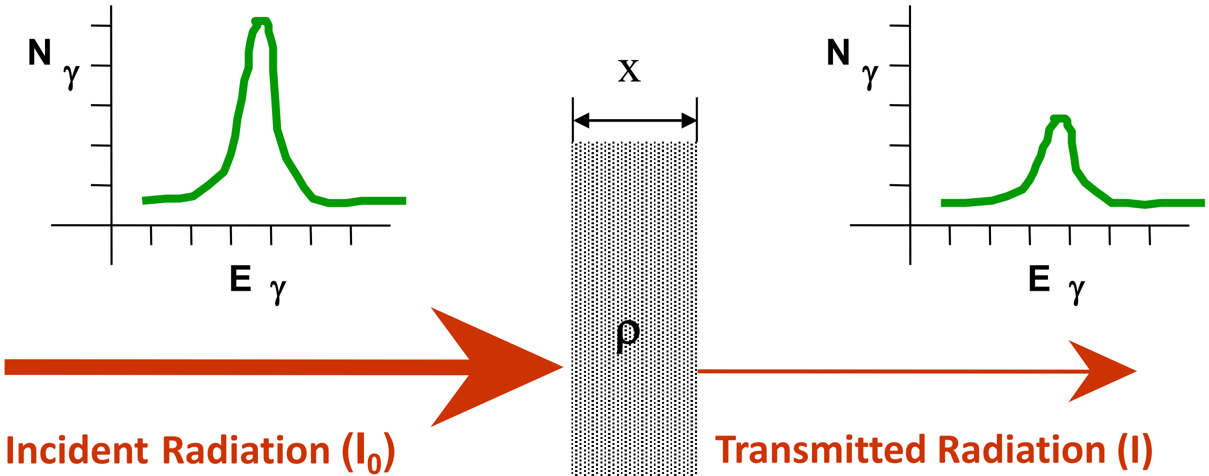


Question Time

- Are lead and water high-Z materials or low-Z materials?

- A) Lead is low Z, water is high Z
- B) Lead is high Z, water is low Z
- C) both lead and water are high Z
- D) both lead and water are low Z

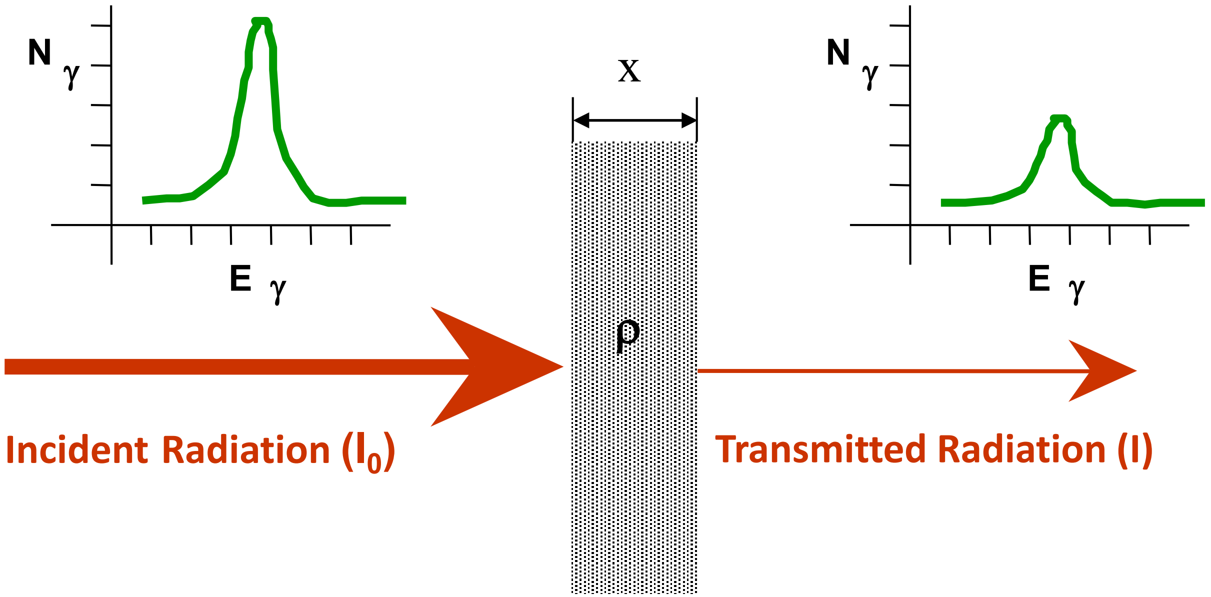
What are Transmission and Attenuation?



The photons that do not interact with the material and still have their full energy are **transmitted**

The photons that DO interact with the material and lose some or all of their energy are **attenuated**
Attenuation is a function of intrinsic material properties (effective atomic number, density) and thickness

What are Attenuation and Transmission?



Attenuation: $I = I_0 e^{-\mu x}$

Transmission: $T = I/I_0 = e^{-\mu x}$

μ = linear attenuation coefficient (cm^{-1})
x = thickness (cm)

Attenuation Coefficients

- Linear attenuation coefficients depend on density
  - Ice, water, water vapor all have different linear attenuation coefficients
  - Units are cm^{-1}
  - Some texts use μ some texts use μ_ℓ

- Mass attenuation coefficients are independent of density
  - Ice, water, water vapor all have same mass attenuation coefficients
  - Units are cm^2/g

$$\mu_{mass} = \frac{\mu_{linear}}{\rho}$$

- When in doubt- check the dimensions
  - exponent must be dimensionless

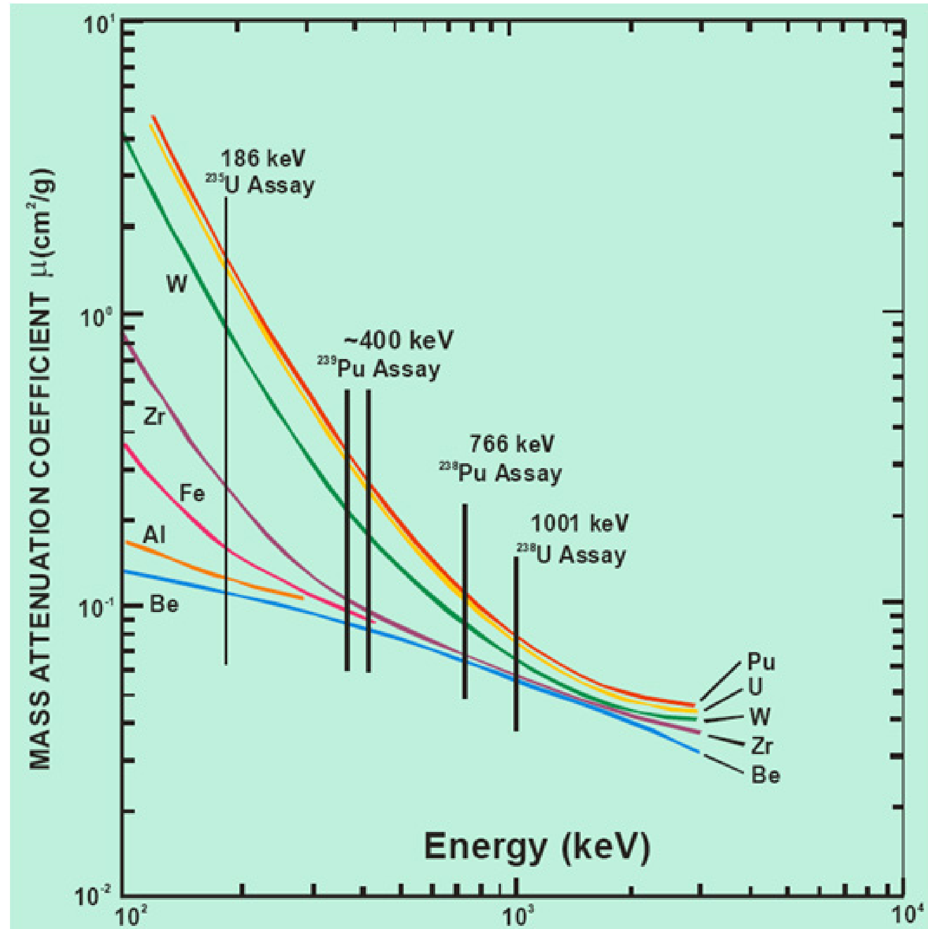
$$\frac{cm^2}{g} = \frac{1}{cm}\frac{cm^3}{g}$$

Attenuation and Atomic Number

At incident photon energies below ~ 1 MeV, the Z of the shielding material matters because this is where the photoelectric effect dominates.

At around ~ 2 MeV the Compton Effect dominates and the probability for interaction becomes independent of Z.

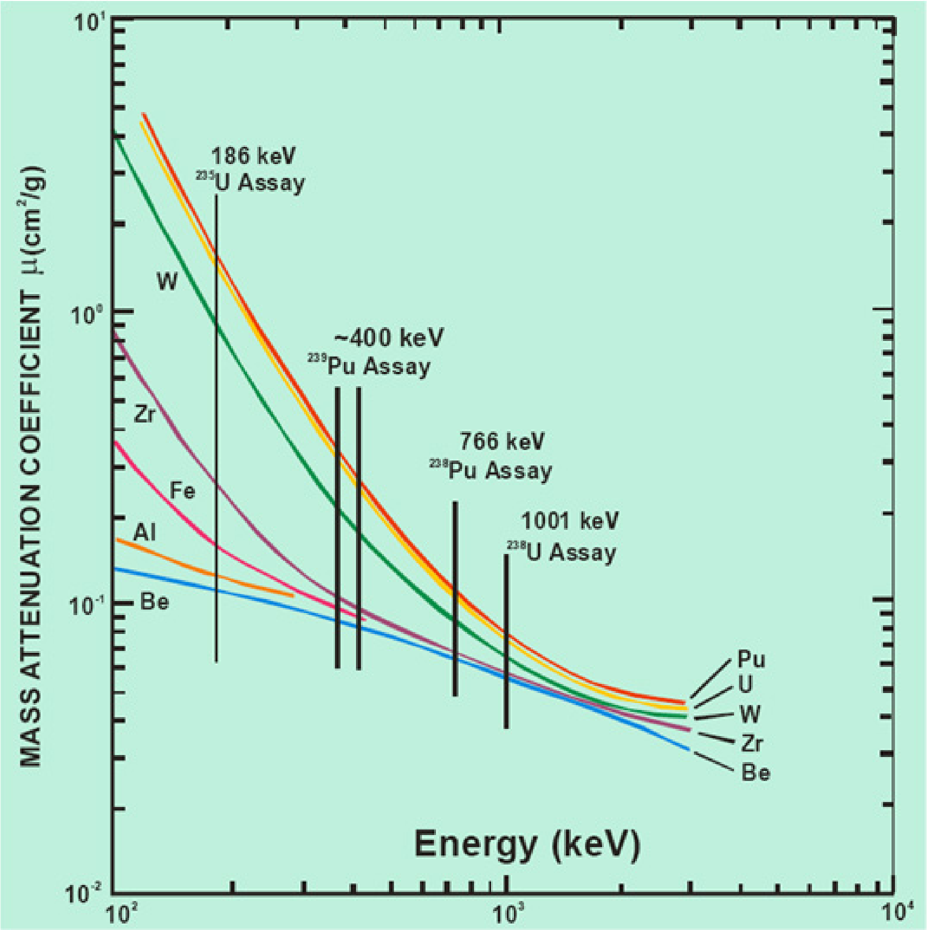
Does the Z of the shielding material matter when pair production dominates?



Question Time

- Which material will attenuate a ~400 keV gamma-ray the most?

- A) Tungsten (W- green)
- B) Aluminum (Al- orange)
- C) Iron (Fe- pink)
- D) Uranium (U- yellow)



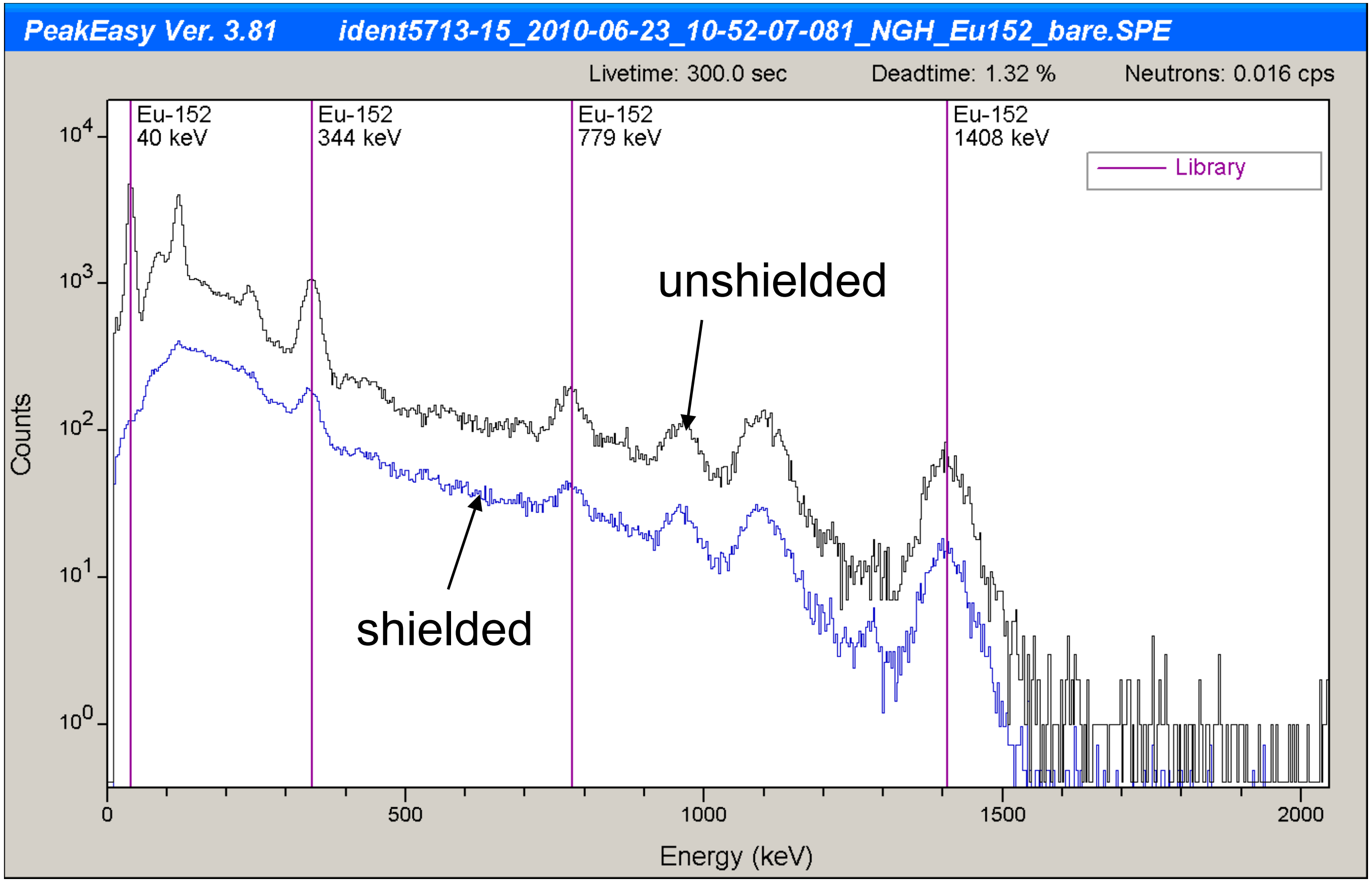
Effect of Shielding in Spectra

- Peak reduction

- Continuum effects

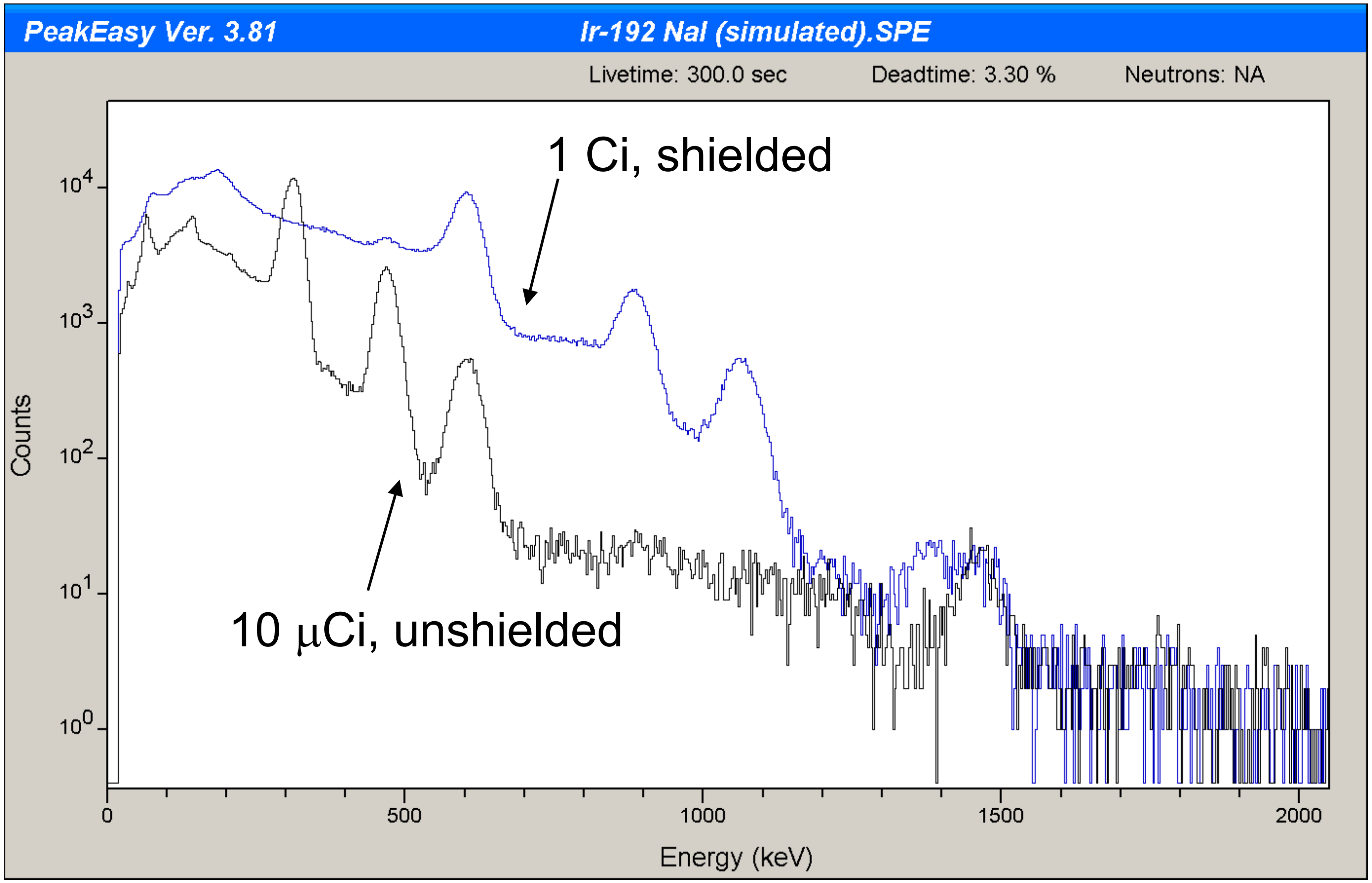
- Fluorescent X-rays from shielding materials

Differential attenuation- low vs high energy peaks



0.75” Fe Shielding Eu-152

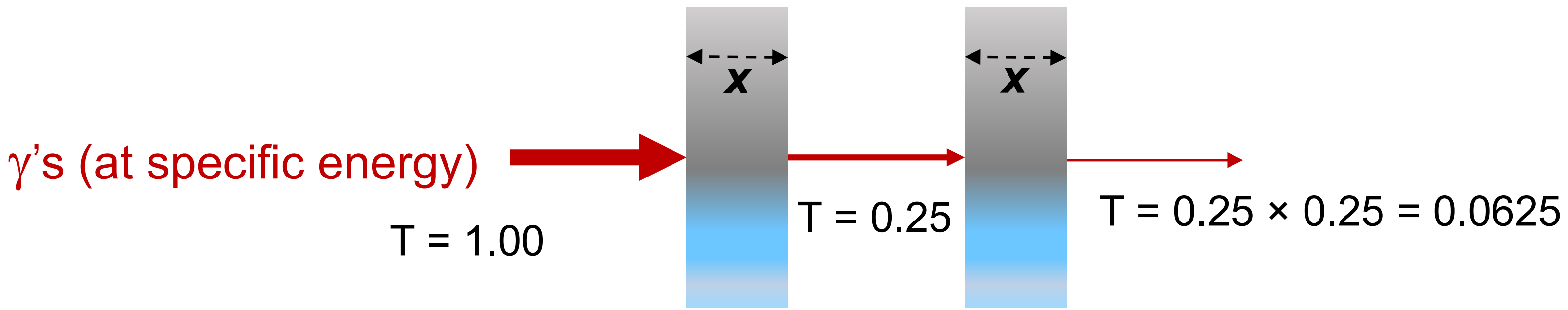
Shielding can change the “shape” of the spectrum



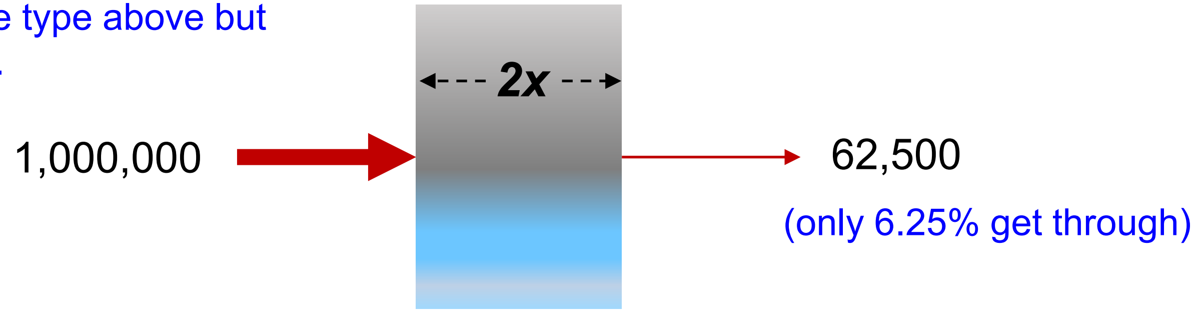
6.5 cm Pb Shielding Ir-192

Transmission is Multiplicative

Shielding of the same type and thickness , ***x***

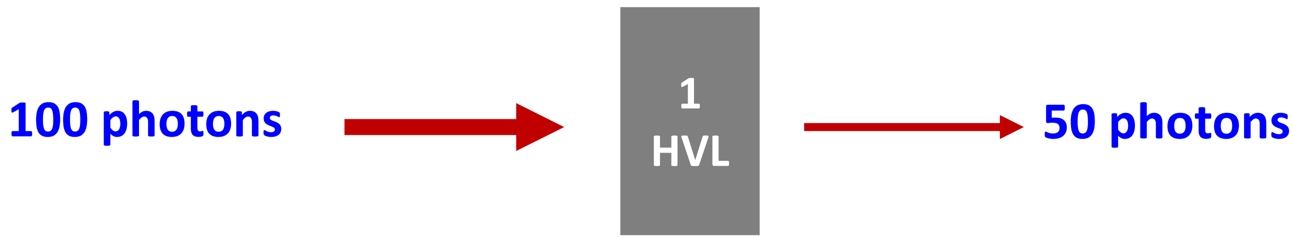


Let's say 1,000,000 gammas at same energy as above are incident upon an attenuator of the same type above but of <u>twice</u> the thickness.



Half-Value Layers

A half-value layer (HVL) is the amount of material required to reduce the radiation intensity <u>at a specific energy</u> by ½.



Energy [keV]	H2O [cm]	Fe [cm]	Pb [cm]	U [cm]
60	3.4	0.070	0.012	0.005
186	5.0	0.6	0.05	0.025
414	6.6	1.0	0.3	0.14
1001	9.8	1.5	0.9	0.5
2614	16.2	2.3	1.4	0.8

Infinite Thickness

What if we use 10 half-value layers?

Transmission, T, through one HVL is 1/2

$$T^{10} = \left(\frac{1}{2}\right)^{10} \cong \frac{1}{1000}$$

Only one photon out of a thousand gets through 10 HVLs. For all practical purposes, we can consider these photons COMPLETELY SHIELDED.

Question Time

- Consider the direct gamma-ray signature of ^{235}U, the peak at 186 keV.

Half Value Layers

Energy [keV]	H2O [cm]	Fe [cm]	Pb [cm]	U [cm]
186	**5.0**	**0.6**	**0.05**	**0.025**

- How much material to essentially shield all gammas from the primary direct gamma-ray signature of U-235, 186 keV?

- A)
- 5 cm water OR
- 0.6 cm Fe OR
- 0.05 cm Pb or
- 0.025 cm U

- B)
- 25 cm water OR
- 3 cm Fe OR
- 0.25 cm Pb or
- 0.125 cm U

- C)
- 50 cm water OR
- 6 cm Fe OR
- 0.5 cm Pb or
- 0.25 cm U

How much shielding to kill 186 keV?

- As an example let's look at what it takes to totally shield the main, direct gamma-ray signature of ^{235}U, that is the peak at 186 keV.

Half Value Layers

Energy [keV]	H2O [cm]	Fe [cm]	Pb [cm]	U [cm]
186	**5.0**	**0.6**	**0.05**	**0.025**

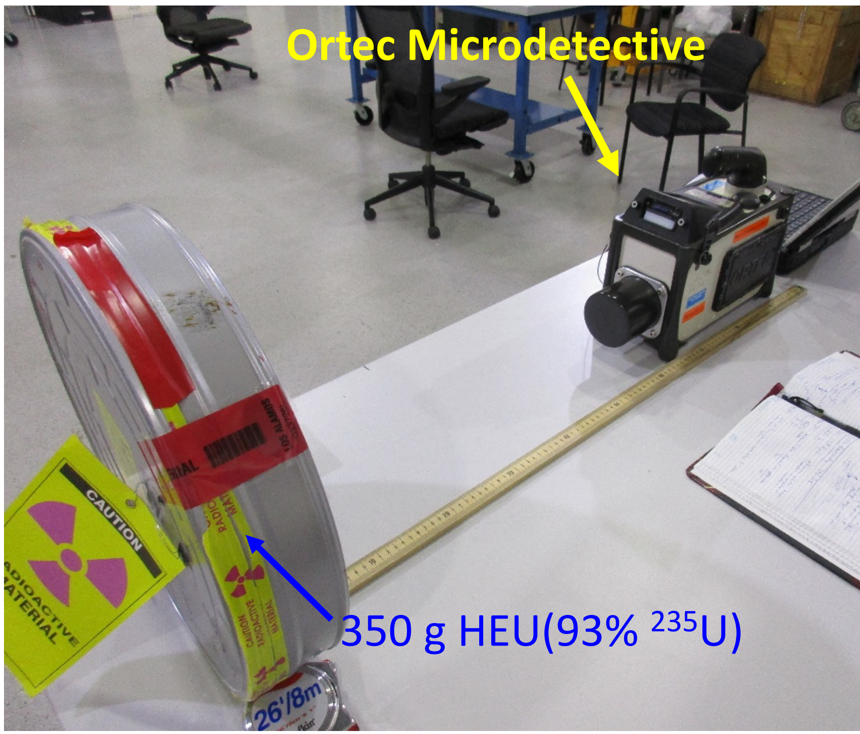
- How much material to essentially shield all gammas from the primary direct gamma-ray signature of U-235, 186 keV?

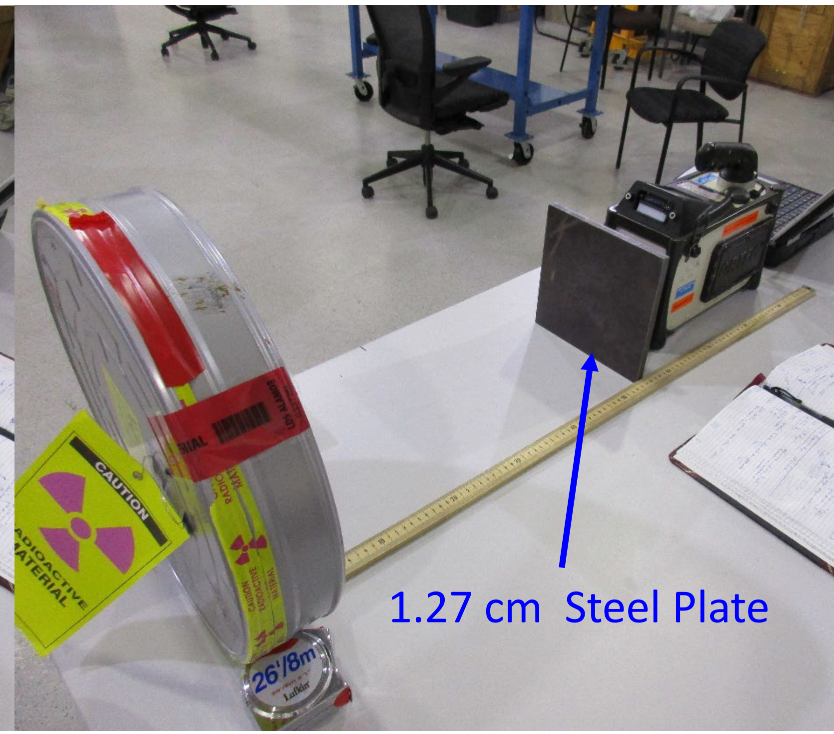
- C) 10 HVL
- 50 cm water OR
- 6 cm Fe OR
- 0.5 cm Pb or
- 0.25 cm U

If you surround HEU with more than 2.5 mm of DU, the only direct ^{235}U gamma rays that you will see will come from the DU itself.

Bare vs. Shielded HEU

Measurements of 9x9” HEU (93% ^{235}U) foils (~350 g total) in a film can were conducted in both bare and shielded configurations.



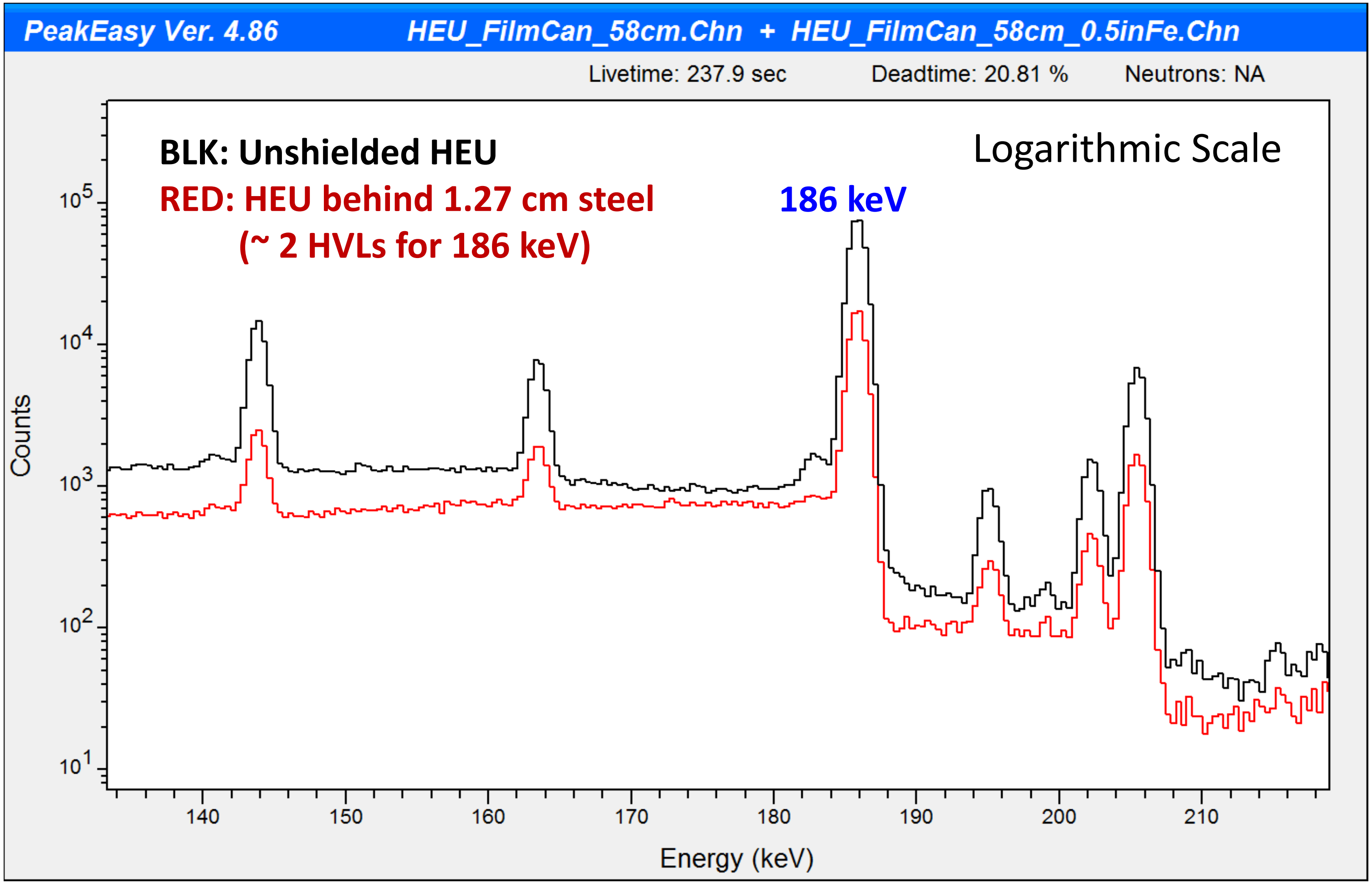


How many HVLs is 1.27 cm Fe for U-235?

Energy [keV]	H_2O [cm]	Fe [cm]	Pb [cm]	U [cm]
60	3.4	0.070	0.012	0.005
186	5.0	0.6	0.05	0.025
414	6.6	1.0	0.3	0.14
1001	9.8	1.5	0.9	0.5
2614	16.2	2.3	1.4	0.8

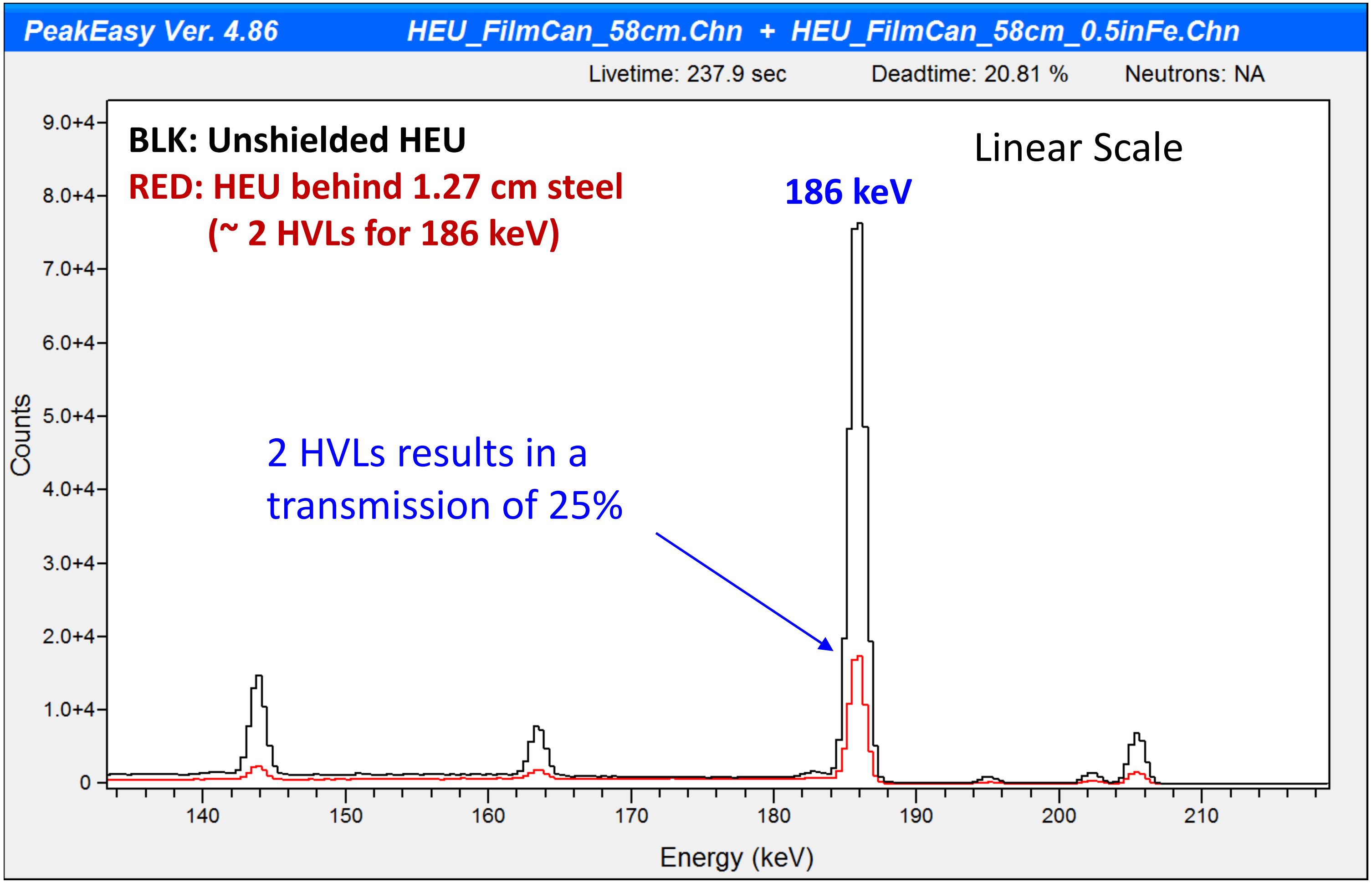
Enter answer in chat

HEU Shielded by 1.27 cm of Steel



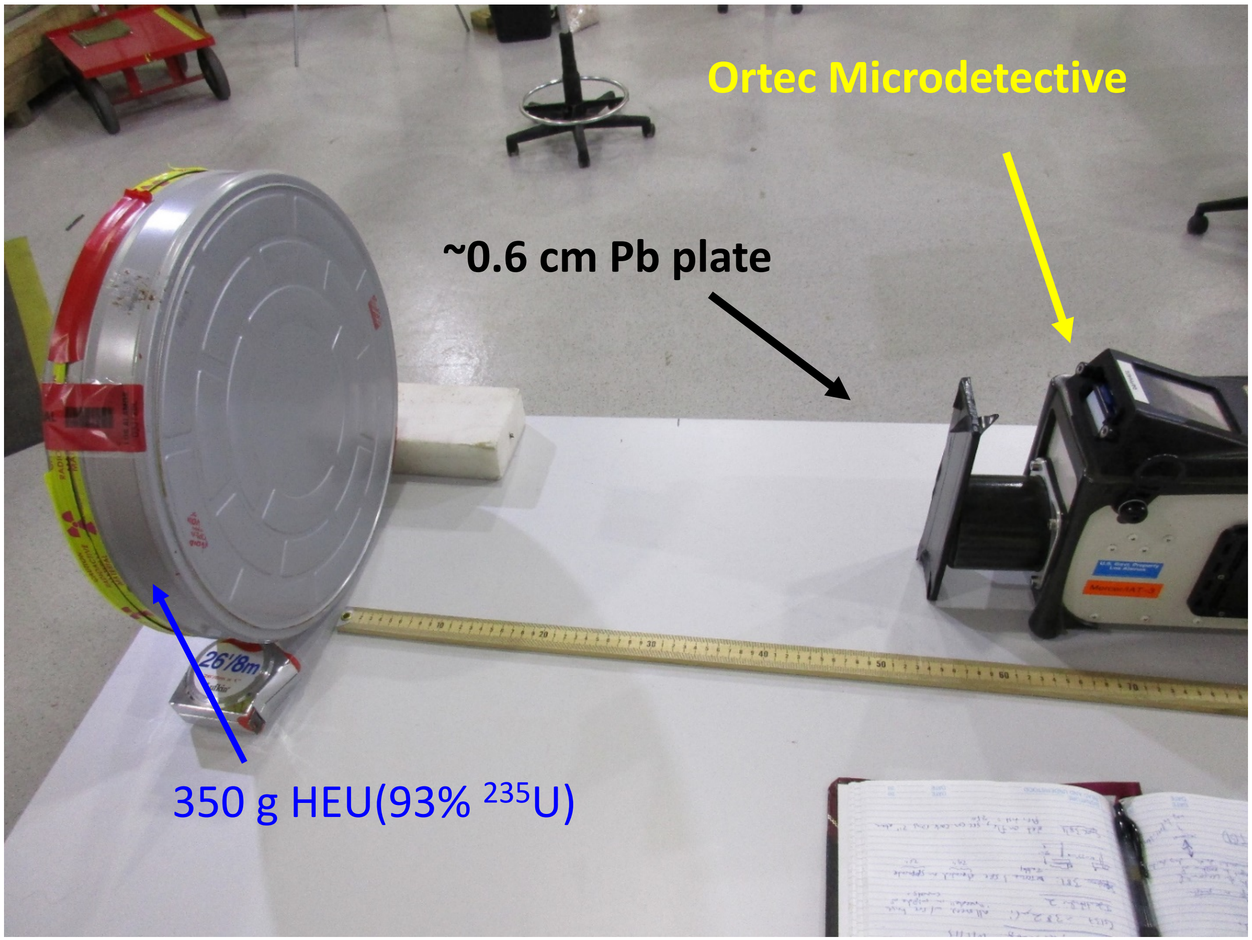
How much is the 186 keV reduced? How well can you "eye-ball" this here?

HEU Shielded by 1.27 cm of Steel

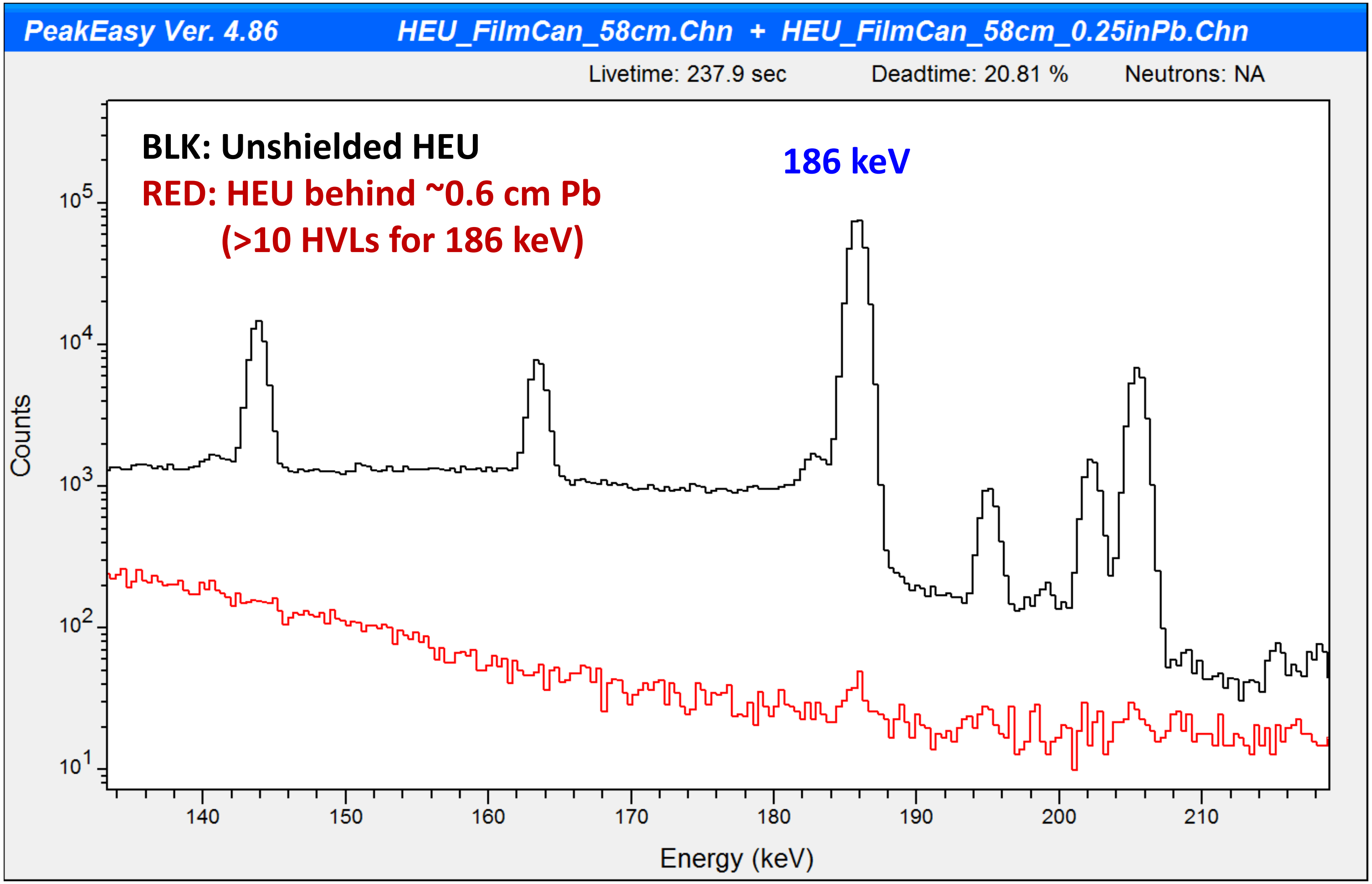


Linear scale makes the reduced transmission very clear.

HEU Shielded by ~0.6 cm of Pb (how many HVLs?)



HEU Shielded by ~0.6 cm of Pb



Effect of Shielding in Spectra

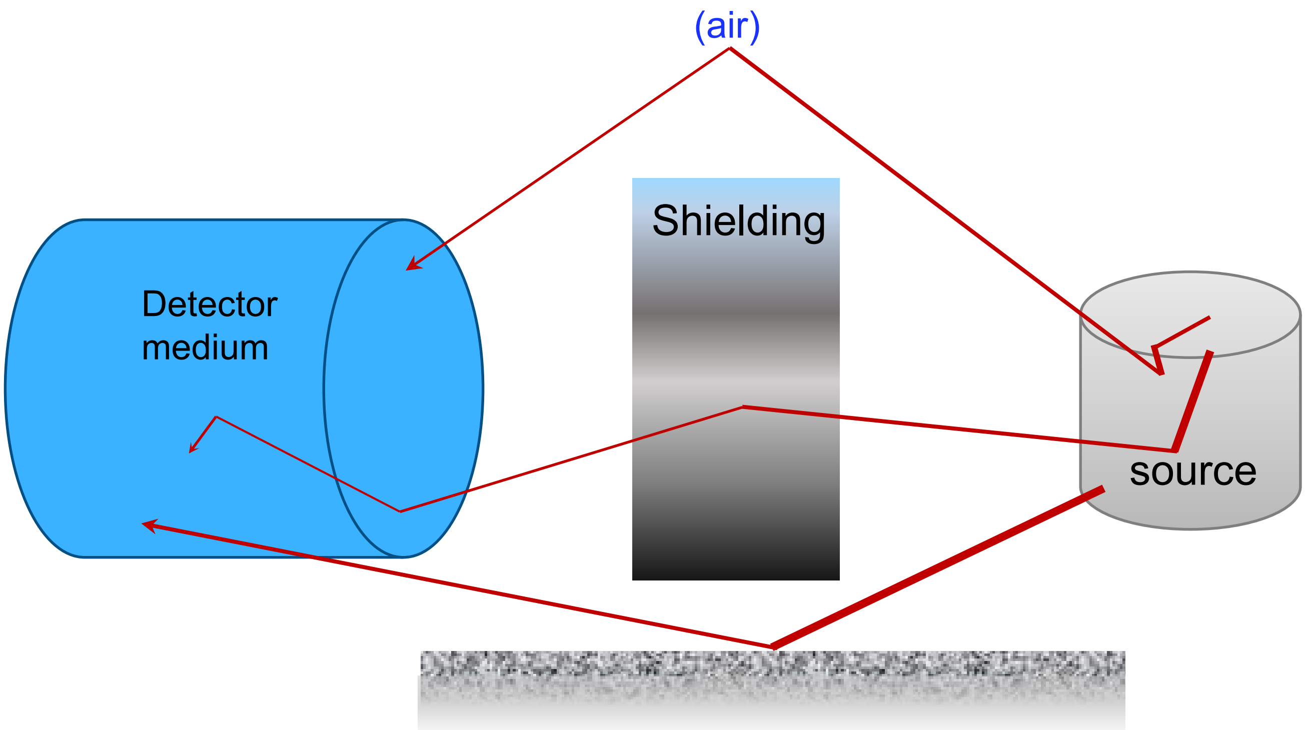
- Continuum effects

Shielding Effects on Continuum

- What produces counts in the continuum?
  - Compton scattering in the detector medium
  - Compton scattering in the source itself
  - Compton scattering in the rest of the environment
    - I.e. ground, air, walls, detector electronics, people, and **shielding**, etc.
- (Aside: How to get zero continuum? Infinite detector medium + point source in a vacuum)
- Scattering produces continuum counts to the **low-energy side** of the full-energy peaks

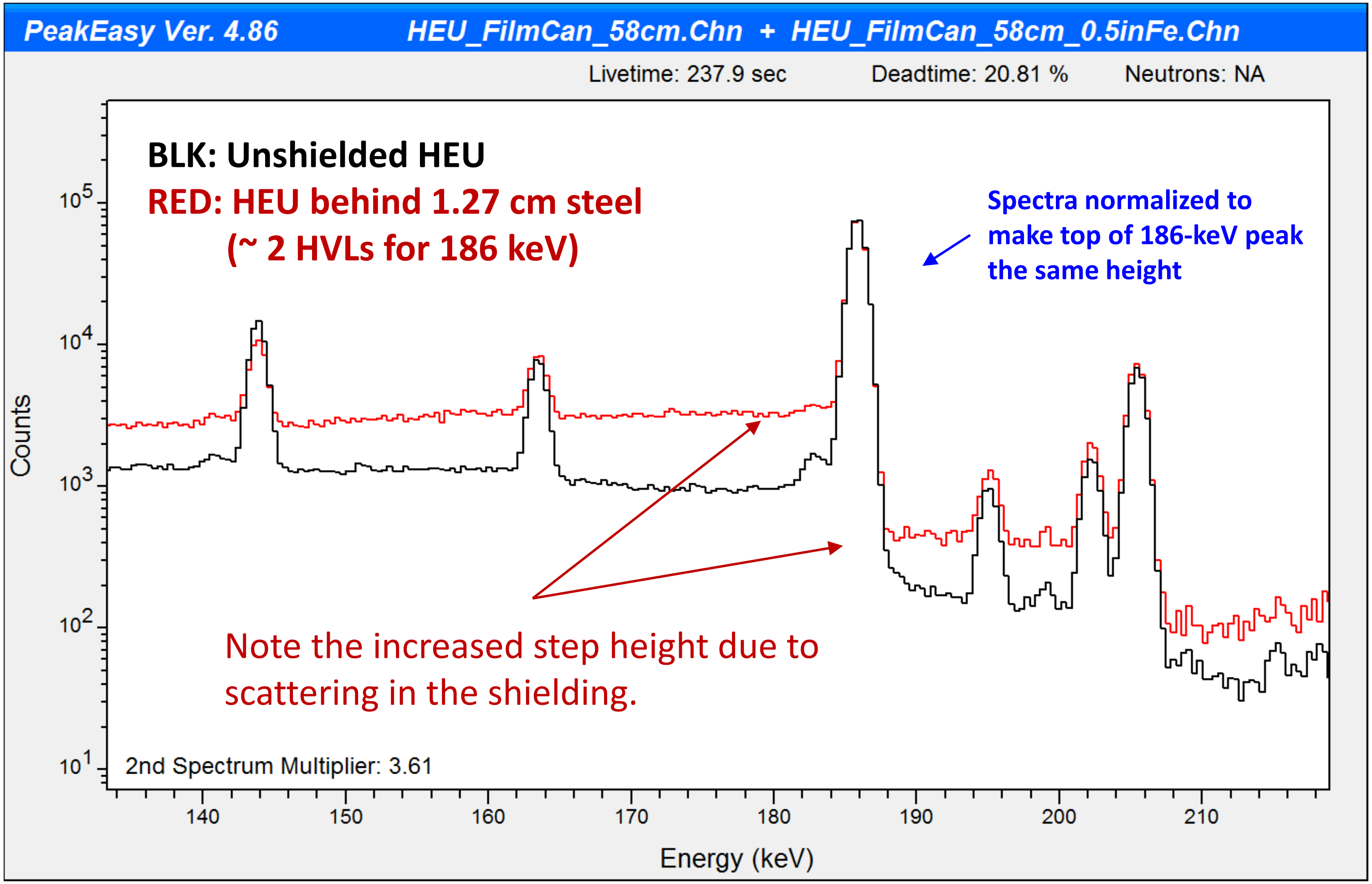
Where does Scattering Occur?

Scattering can occur in the detector medium, in the air, in the source itself, in shielding, etc.



If the source is point-like (e.g. 10 uCi of ^{137}Cs) then 'self-attenuation' is minimal. But not so for extended / distributed sources like SNM or the natural background

Continuum "step"



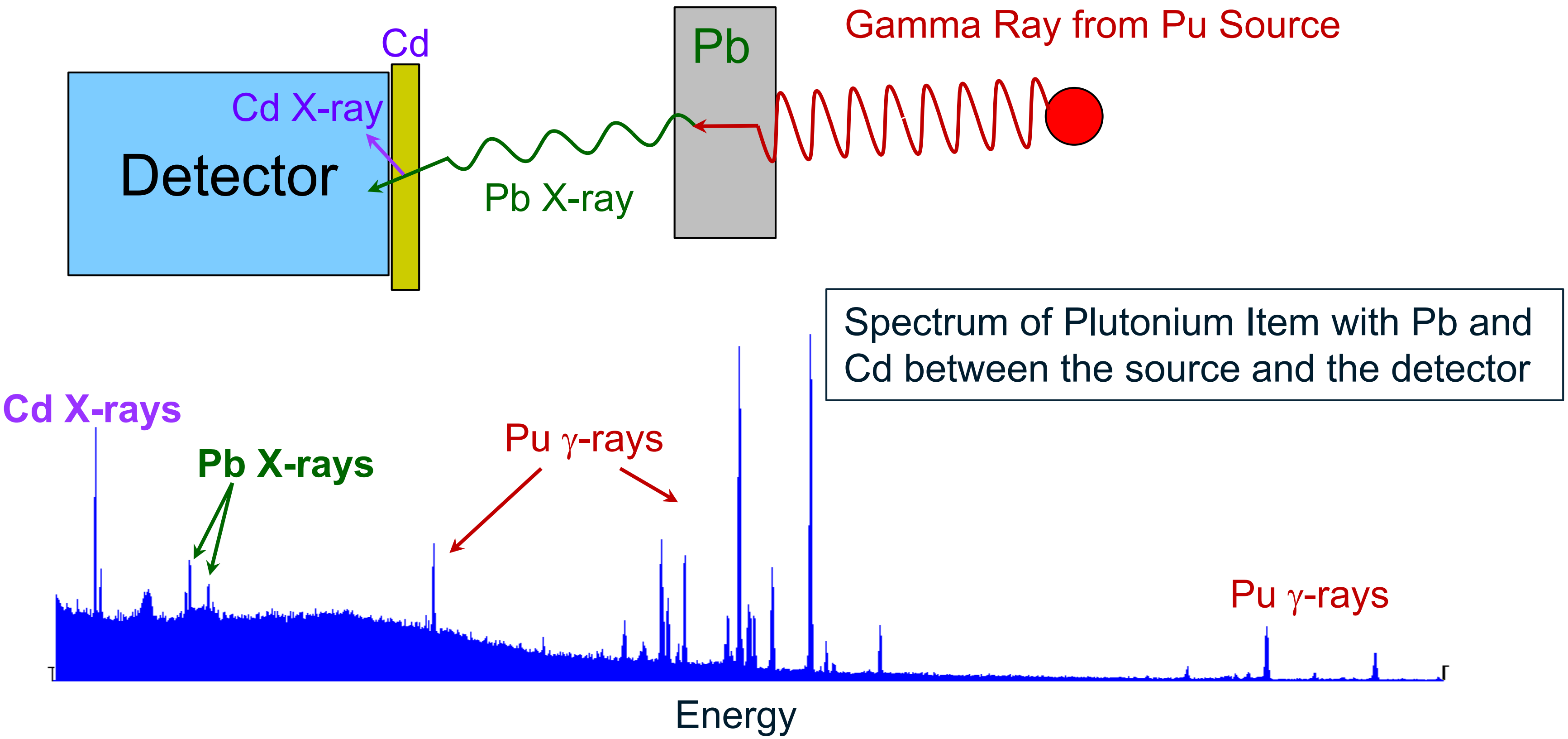
caused by multiple and small-angle scattering proportional to local peak amplitudes (areas)

Effect of Shielding in Spectra

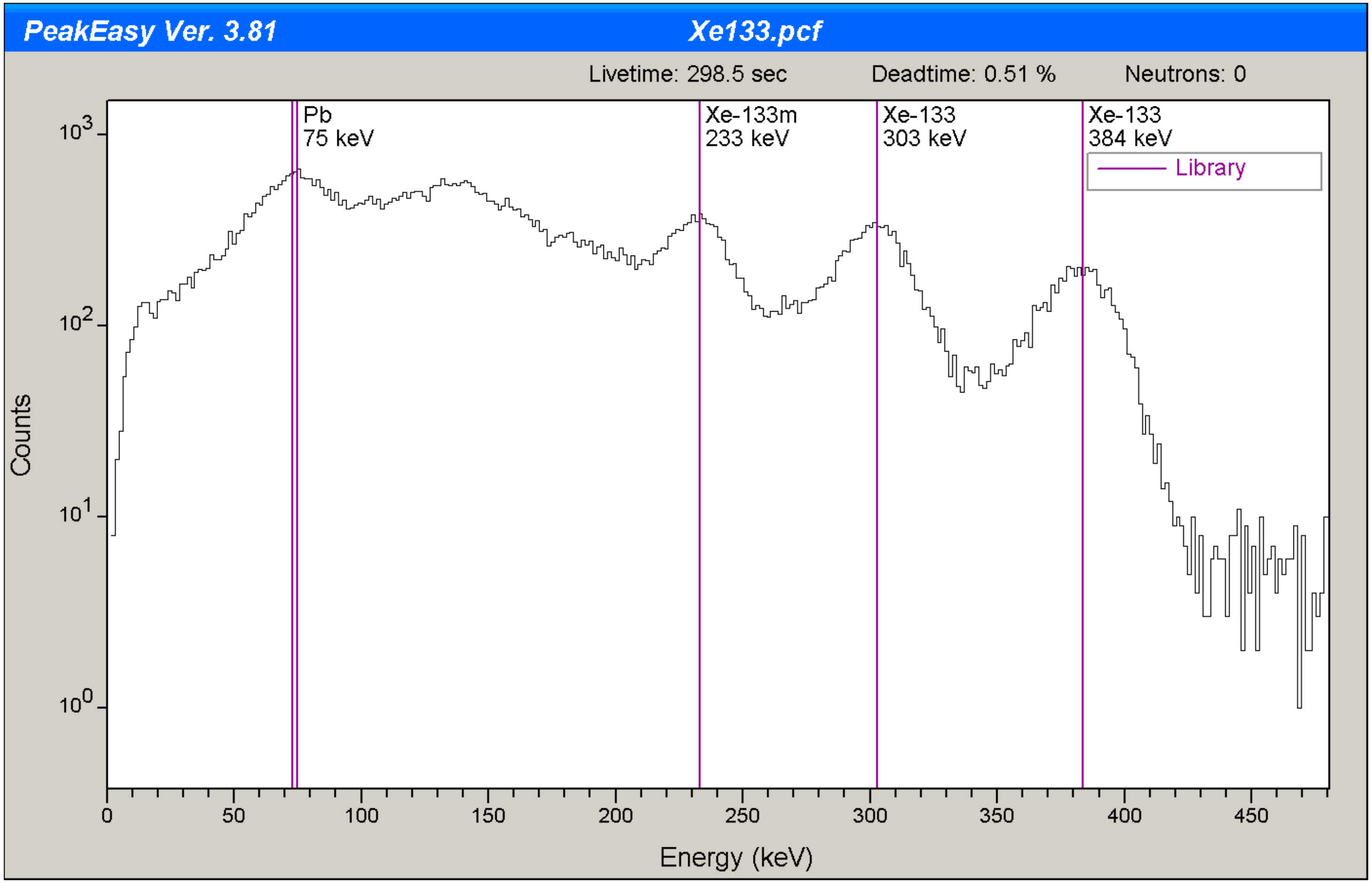
- Fluorescent X-rays from shielding materials

X-Ray Fluorescence (XRF)

Gamma rays from the source ionize the attenuating material via the photoelectric effect (shown) or the Compton effect, resulting in the emission of characteristic x rays.

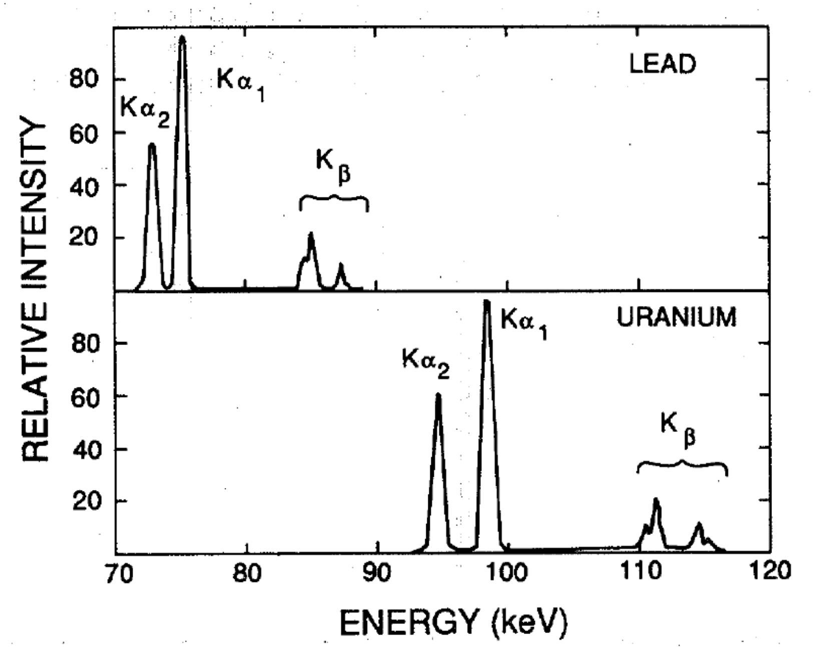


Pb XRF in Low Resolution Data

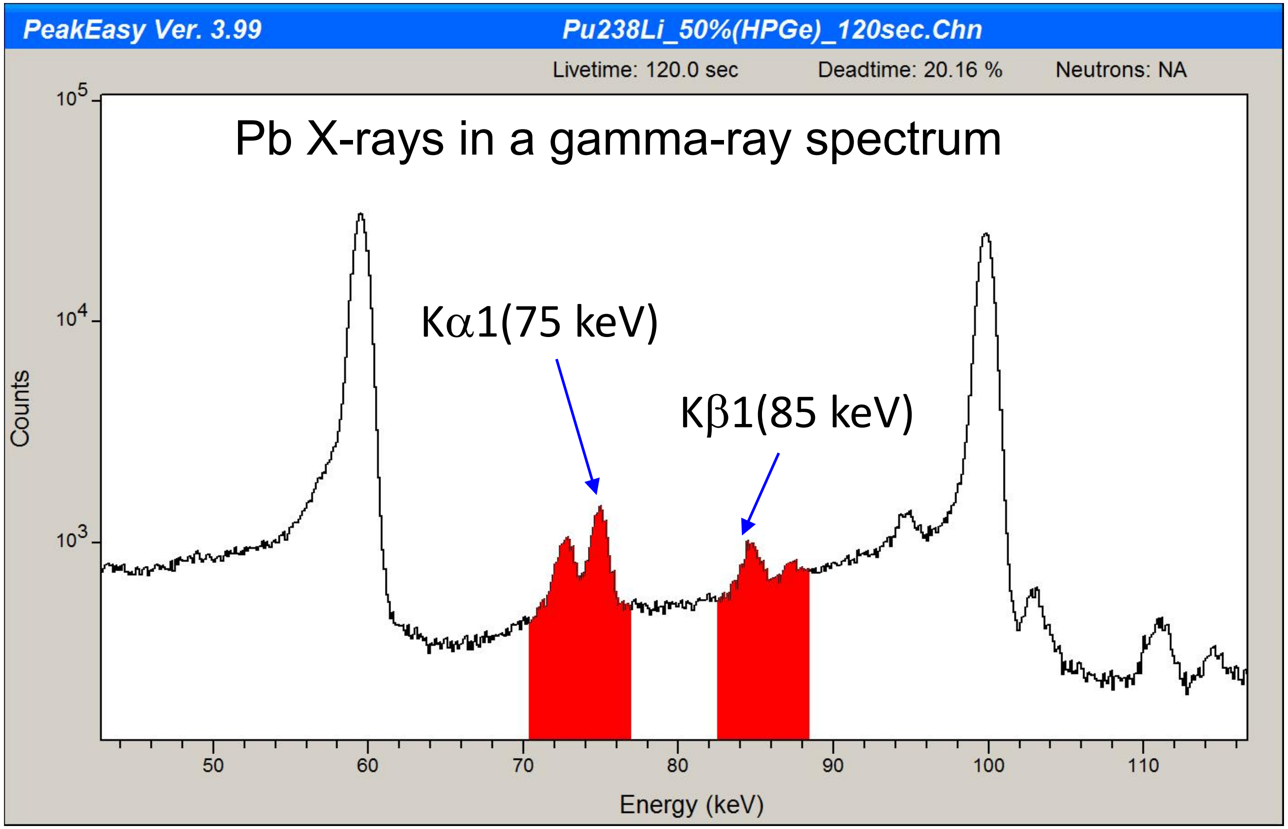


X ray Peak Patterns (High Res.)

Since all elements build on the same inner-shell electron structure, peaks from characteristic x rays exhibit the **same pattern**, only shifted by energy, within the limits of detector resolution.



Pb XRF in a HPGe Spectrum



What indicates that these x rays might be from a Pb collimator and not Pb shielding the source? (answer in chat)

Making Predictions

- Low-E Photons + High-Z Shield
  - E < ~200-ish keV, Z > 50-ish
  - More photons will be absorbed via the photoelectric effect
  - Contribution to Compton continuum will be minimized
- Med/High-E Photons (100’s keV – a few MeV)
  - E > ~500-ish keV, Z dependence is less
  - Compton scattering will dominate
    - More continuum, more step features
- High-E Photons (E several MeV)
  - Pair Production (especially for high-Z materials)

Summary

- Attenuation is a function of the incident gamma-ray, material properties, and the thickness of the material
- Half Value Layers (HVL) are a useful concept for estimating how much a given thickness of material will impact transmission of gamma-rays
- Shielding impacts spectra in predictable ways
  - Reduce peak height, with low energy peaks impacted more than high energy peaks (in extreme, to the point of altering the “shape”)
  - Increased scattering gives counts in the continuum and increased steps
  - Characteristic x-rays from shielding materials
- We can use clues in the spectrum to infer information about the source’s local environment